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14. ABSTRACT
The aim of this proposal is to demonstrate the key elements needed to construct a logical qubit in diamond by exploiting the remarkable quantum properties of the nitrogen-vacancy (NV) optical centre. Specifically, the focus of the work was to address the materials and fabrication issues. We have demonstrated (i) that individual NV qubits can be fabricated by ion implantation with long coherence times (> 350 microseconds at room temperature), (ii) electrical control of the optical output of each individual centre is achievable via the Stark shift, (iii) coherent population trapping of ensembles and single NV centres allowing for all-optical control of qubit operations and (iv) that waveguides, cavities and photonic band-gap structures can be fabricated in single crystal diamond. We have thus demonstrated a nanofabrication tool-kit for diamond which is sufficiently robust and mature to justify future investment in the design and implementation of a scalable quantum computing architecture for diamond.

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ARO Final Report

Short term Innovative Concept Proposal: Quantum Computing in Diamond

W911NF-05-1-0284

Abstract:

The aim of this proposal is to demonstrate the key elements needed to construct a logical qubit in diamond by exploiting the remarkable quantum properties of the nitrogen-vacancy (NV) optical centre. Specifically, the focus of the work was to address the materials and fabrication issues. We have demonstrated (i) that individual NV qubits can be fabricated by ion implantation with long coherence times (> 350 microseconds at room temperature), (ii) electrical control of the optical output of each individual centre is achievable via the Stark shift, (iii) coherent population trapping of ensembles and single NV centres allowing for all-optical control of qubit operations and (iv) that waveguides, cavities and photonic band-gap structures can be fabricated in single crystal diamond. We have thus demonstrated a nanofabrication tool-kit for diamond which is sufficiently robust and mature to justify future investment in the design and implementation of a scalable quantum computing architecture for diamond.

Introduction:

This report covers the period of the STIC grant from its inception on May 15, 2005 through to 30 September 2006. However the funding period of the grant was much shorter than this: 15 May 2005 - Jan 14, 2006, with no funds received beyond this date. Thus the progress demonstrated here represents the progress obtained with only 8 months of ARO support. Nevertheless, excellent progress was made with most of the original goals of the 2 year STIC proposal being accomplished. The grant brought together a team of researchers at the University of Melbourne, Hewlett-Packard, Texas A&M, and the University of Stuttgart and has resulted in 14 refereed publications including one paper in Nature Physics, two Physical Review Letters, one paper in Advanced Materials and three Applied Physics Letters. This report covers the following areas and references are to the publications listed at the end of the report.

Brief Statement of the problem addressed: Diamond is attractive for use in quantum electronics applications because the three principal sources of dephasing in solids: free carriers, optical phonons, and nuclear spins, are all strongly suppressed. Its wide band gap (5.4 eV) and high Debye temperature (2400K) result in populations of intrinsic carriers and optical phonons, respectively, that are effectively zero even at room temperature. Its low density of nuclear spins, typically 99% of the nuclei being ^{12}C with total spin vector I = 0, result in much weaker spin dephasing than in most semiconductor materials. Work is underway to grow isotopically pure ^{12}C diamond in which no nuclear spins will be present, thus making ‘diamagnetic diamond’, in which electron spin dephasing times of several milliseconds are predicted. Much of the work reported here involves the nitrogen-vacancy defect, a substitutional nitrogen atom on an adjacent lattice site to a vacancy. Many of the quantum properties of this centre have been well established; perhaps the most important is that single NV centres can be

addressed optically. Single spin read-out, one and two qubit operations and long coherence times have all been convincingly demonstrated.

This project tackled practical questions regarding the use of diamond as a platform for applications in quantum information processing. We aimed to establish (i) whether single NV centres could be created by ion implantation and whether these centres would have sufficiently long coherence times to be useful for QIP, (ii) Stark shift control of single NV centres, (iii) all optical control of the quantum state of the NV centres via coherent population trapping and (iv) nanofabrication of waveguides, mirrors and other optical components within single crystal diamond designed to meet the requirements of coupling NV centres to optical cavities.

The report covers the following topics.

1. Fabrication and characterization of NV centres in diamond using ion implantation.
   1.1 Creation of NV centers using ion implantation
   1.2 Implantation of N_2 dimers to create pairs of coupled spins.
   1. 3 Coherent population trapping in NV diamond ensembles and single centres.
2. Stark shift tuning of single NV centres
3. Fabrication of waveguides in single crystal diamond.
4. Future Outlook

1. Fabrication of NV centres in diamond using ion implantation.

1.1: Creation of NV centres using ion implantation

In bulk diamond, ion implantation offers the possibility of direct placement of NV centers with nanometer scale precision using technologies developed for the placement of single P donors in silicon. Two alternative routes are available for the creation of NV centers. The first method involves implantation to create vacancies in nitrogen-rich type Ib diamond. Annealing above 600ºC causes the vacancies to migrate to the pre-existing substitutional nitrogen to form NV centers. By performing ion implantation through a micron scale mask, controlled placement becomes possible. A fluorescence image showing an NV array generated by this method is shown in Fig. 1a. Optimization of the dose and annealing parameters for creation of such centres are thoroughly reviewed in [8]. Scaling this to produce small numbers of NV centers can be accomplished by irradiating through nanoscale, rather than micron scale masks. This method provides a rapid and efficient route to making the large arrays required by a defect-tolerant architecture.

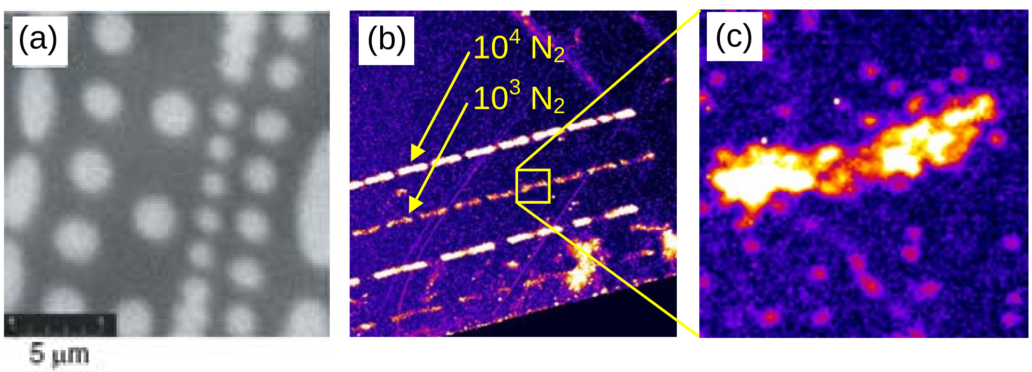

Fig. 1: Confocal microscope images of NV centers created in bulk diamond through ion implantation of (a) gallium ions in type Ib diamond; (b,c) nitrogen ions in type IIa diamond.

The second method involves the direct implantation of nitrogen ions into type IIa diamond containing low concentrations of nitrogen, followed by thermal annealing. Since one of the main causes of decoherence in NV centers is spin flips due to the presence of excess nitrogen, the use of high purity crystals is essential to increase decoherence times. Figs.1b,c show confocal microscope images of NV centers created through nitrogen implantation. In Fig. 1c, individual NV centers are resolved. By implanting ^{15}N ions instead of ^{14}N, it is possible, through examination of the hyperfine structure to distinguish between NV centers formed from implanted and background nitrogen [5]. The use of ^{15}N implantations allows us for the first time to provide a quantitative estimate of the yield, i.e. the probability that an implanted N atom will result in an observable NV centre. Although, in [5] the yield is reported to be only 2.5%, we already have strategies in place to improve this by optimiziation of the relevant parameters which are the depth of implant (i.e. the proximity to the surface) and the temperature of the implantation. Preliminary measurements would indicate that we may expect to improve the yield to circa 20%. Although this route is more demanding, we expect the yield of acceptable NV centers to be significantly higher than the previous approach.

1.2: Implantation of N_2 dimers to form coupled pairs of spins

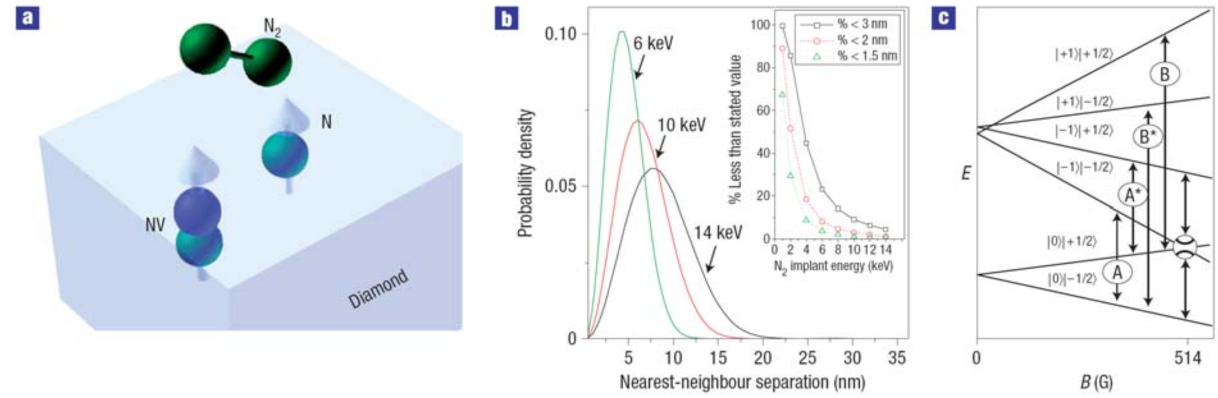

Figure 2: Fabrication of coupled spin pairs in diamond. (a) N2 dimer implantation to create NV/N coupled pairs, (b) mote-carlo simulations of the nearest neighnour simulations as a function of implant enegy and (c) calculated dependence of the energy spacings of the NV/N coupled systems on applied Magnetic Field. [9]

A major challenge for the use of NV in diamond is the demonstration of coherent coupling between single centres. We have recently shown [9], that a single pair of strongly coupled spins in diamond (specifically an NV centre and single substitutional N) can be optically initialized and read out at room temperature. To effect such strong coupling, close proximity of the two spins is required, but large distances from other spins are required to avoid deleterious decoherence. The scheme developed to reconcile these competing requirements is shown in Figure 2a in which coupled pairs of spins are created by implantation of N_2 dimers instead of N atoms. Figure 2b shows Monte-Carlo simulations of the distribution of interpair spacings as a function of implant energy and Figure 2c shows the expected energy level spacings resulting from NV-N coupling. Figure 3 show the experimental verification of the splitting expected from NV/N coupling. The T2 time for these coupled centres was measured to be 0.35ms. This work was reviewed by Prof John

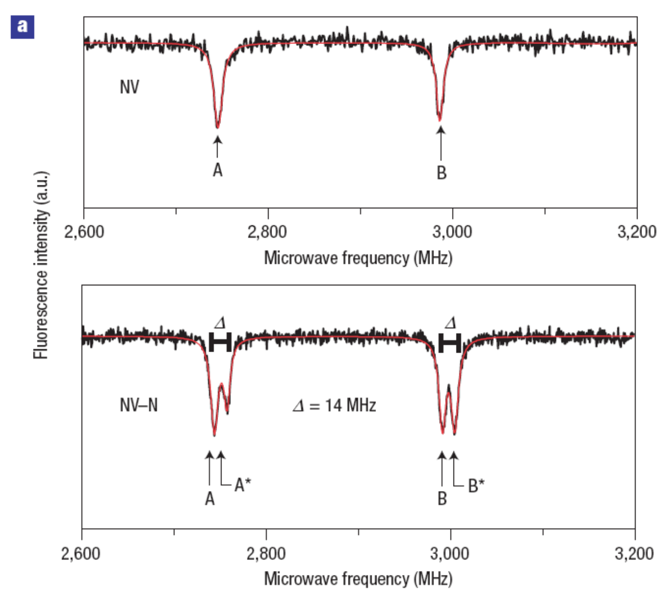

Figure 3. Magnetic Resonance on NV-N spin pairs showing single NV centres (top panel) and NV/N coupled pairs (bottom panel). The labels on the peaks refer to transitions shown in Figure 2c. [9]

Morton (University of Oxford), who describes the impact of this result as having '…*thrust it [diamond], towards the very forefront of the candidates for solid state quantum computing'*[1].

1.3 Coherent Population Trapping in NV diamond

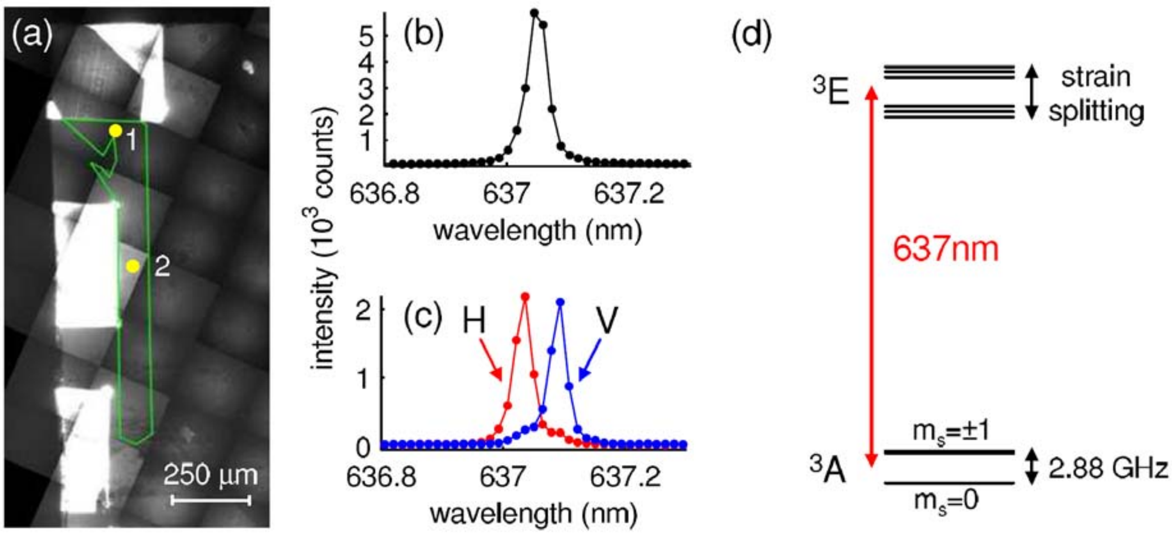

Figure 4, (a) PL image of the sample. The bright regions are implanted to create strain at regions 1 and 2. (b) splitting of the NV ZPL due to strain, and (c) schematic of induced strain splitting of the excited state.

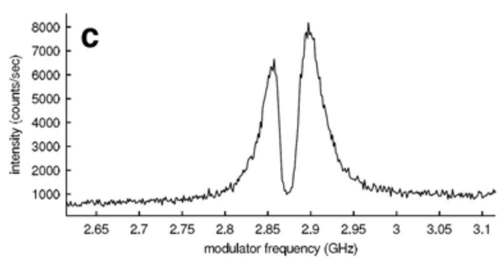

***Figure 5. PL intensity from a single NV emission as a function of modulator frequency. The dip at 2.88 GHz is unequivocal evidence for coherent population trapping in a single NV and demonstrates that all-optical control of single spins is possible in diamond*.**

We have observed coherent population trapping at zero magnetic field for NV centres under optical excitation. The behaviour was found to be [10] highly sensitive to strain. The strain field was deliberately created by deep MeV ion implantation an area adjacent to that used for measurement (see figure 4). The measurements employ two excitation lasers matched to the 2.88GHz crystal-field splitting of the NV ground states. The technique has been further refined so as to be able to demonstrate coherent population trapping of a single NV centre [15]. These results demonstrate the feasibility of all optical control of single spins in diamond.

It is clear that obtaining a deeper understanding of the the excited state structure is critical to the use of NV diamond for QIP. An important review on the properties of NV diamond was completed [12] and measurements of the fundamental properties of NV diamond have continued to be investigated [13,14].

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[1] J. Morton, Nature Physics, **2**, 265, (2006)

2. Stark Shift control of single NV centres.

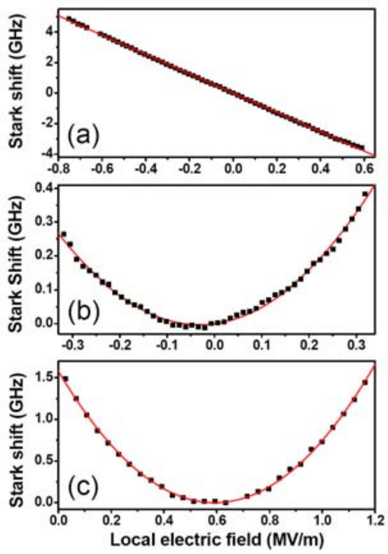

Figure 6: Stark shift of single NV centres in diamond. Linear and quadratic Stark shifts are observed. [11]

A key milestone towards a scalable architecture in diamond is the demonstration that it is possible to Stark shift tune the resonant frequency of single NV centres via the application of a voltage to electrodes registered to these centres. Prior to this STIC proposal there was no convincing evidence that it was possible to achieve this experimentally for a single NV, although an estimate of the size of the expected Stark shift could be deduced from measurements of ensembles.

We have now succeeded in measuring the Stark shift due to single NV centres in diamond [11]. Lifetime limited optical excitation have been observed at room temperature, with the lines displaying unprecedented stability over many seconds and excitation cycles. Figure 6 shows the Stark shift in GHz as a function of local electric field for a number of different centres, displaying both linear and quadratic Stark shifts.

At present it is not clear why some centres display linear stark shifts and some quadratic shifts, and this is being investigated at present. However, it is clear that this it is possible to obtain the required spectral stability to spectrally tune NV into resonance with optical cavities or other quantum systems and hence paves the way towards applications of diamond in QIP.

3. Fabrication of Waveguides in Diamond.

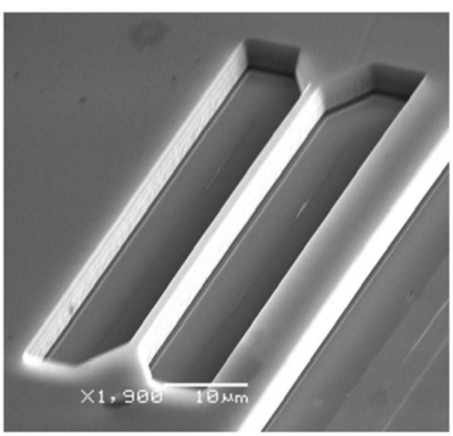

Figure 7. Cantilever hewn from single crystal diamond using a combination of MeV ion implantation, FIB milling and acid etching.

A new method for the fabrication of free standing micro-structures in bulk single-crystal diamond was recently demonstrated [3,7]. The method is inspired by the “diamond lift-off” technique and takes advantage of the fact that, by means of ion implantation, it is possible to induce a phase transformation from diamond to a selectively etchable phase (the sacrificial layer). The sacrificial layer is created by the transformation induced by MeV ions which deposit most of their energy at the end of range, creating a spatially well-defined disordered region. These conditions are by no-means restrictive, and control of the energy, fluence, and implant species will all determine where most of the lattice transformation occurs, and this has been studied in more depth previously. Hence it is possible to control the vertical location of the sacrificial layer to sub-micron resolution.

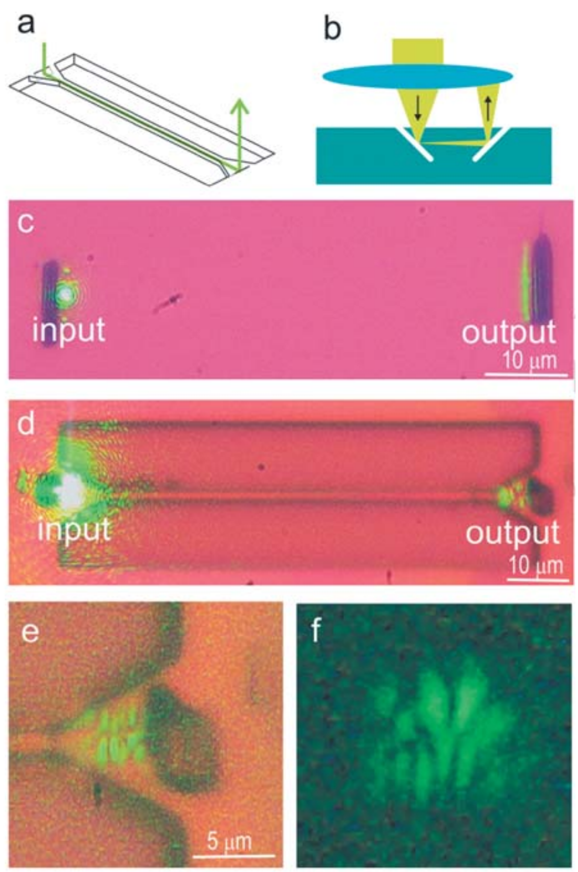

Figure 8: Optical characterization of the waveguide structure shown in Figure 7. Input output mirrors are realized by 45^0 angle cuts in the diamond (a,b,c). Such mirrors have been fabricated at the end of the waveguide (d)m resulting in multimode transmission through the waveguide (e,f).

A test structure comprising a free standing bridge waveguide in single crystal diamond is shown in the SEM image in Fig 7. The remarkable smoothness of the bottom surfaces after lift-off is due to the abrupt damage threshold for phase transformation upon annealing that leads to a sharp interface between diamond and the sacrificial layer. The optical characterization of the device is demonstrated in Fig 8, which shows the multimoded output from the waveguide. With the same procedure, a range of three-dimensional structures (cantilevers, cavities, beamsplitters, etc) can be created in bulk diamond with sub-micrometer spatial resolution, and these are currently being investigated for single mode operation which will require the thickness of the layer to be circa 200nm. A more detailed description of the micromachining technique, together with an extensive characterization of the material properties of the structures during the fabrication process, can be found in [7].

These techniques are now being exploited to fabricate more complex structures including microdisks and photonic crystal cavities. Some of the latest structures to be fabricated are shown in figure 9.

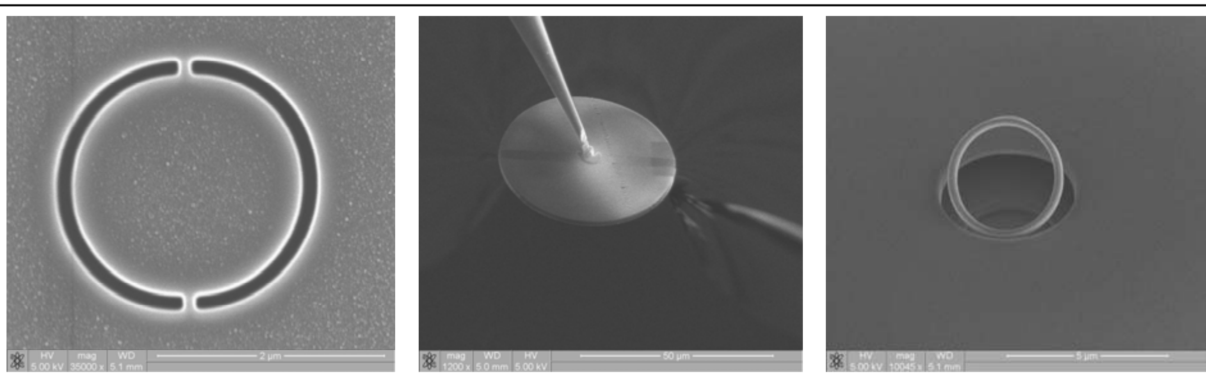

Fig. 9 SEM micrographs of diamond microcavity structures: (a) A disk cavity 2µm in diameter and 200 nm thick. The 200 nm film remains attached to the diamond substrate only at the edges (not shown), so the cavity is supported only by the narrow bridges at the top and bottom of the picture; (b) lifting off a 40µm diameter, 1µm thick film of single crystal diamond after separation in the FIB; (c) the world's smallest diamond ring: a 5µm diameter whispering gallery mode resonator. [Olivero and Waldermann, unpublished].

4. Outlook and summary:

The motivation for the use of diamond in quantum computing lies primarily in the availability of an ‘optical handle’ i.e. a reliable and robust optical method for single spin read out and qubit control.

This STIC proposal has shown how it is possible to translate this potential into usable devices. Specifically, the key elements needed to engineer qubits in diamond require (i) sourcing and characterizing materials of sufficient purity, (ii) the ability to pattern individual NV centers in diamond and register them to electrical gates, (iii) the ability to tune the optical output of a single NV using the Stark shift, (iv) the ability to fabricate waveguides input-output mirrors in single crystal diamond and (v) establishing the capability for coupling the NV centers to cavities/photonic band gap structures. Excellent progress has been made on all fronts which has been documented above. To combine these qubits into a full quantum architecture will require further development and application of the philosophy of defect tolerance in the architecture: an approach that NV diamond appears especially suited to. The lift off technique has been shown to be capable of creating waveguides, mirrors and other optical structures. The data shows that it will be possible to Stark shift tune individual NV centres into resonance and provided that the required surface roughness can be attained, it should be possible to use a combination of lift-off and FIB techniques to create photonic band gap cavities in diamond. Sophisticated, but entirely realizable primitives and architectures have been theoretically modeled that provide guidance to the sort of interesting structures and devices which can be fabricated in the near future. Finally, manufacturers such as Element Six have begun to produce single crystal diamond plates with sub ppb N and B impurities and at a level of perfection never before achieved. Soon isotopically pure materials are expected to be available to diamond researchers. The availability of such source materials, coupled with the nanotechnology toolkit developed as part of this STIC proposal provides a strong motivation for the pursuit of diamond based QIP.

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1. VLSI Quantum Computer in Diamond," P Hemmer, S Prawer, E Trajkov, J Wrachtrup, F Jelezko, N Manson and M Sellars, **Photonics West 2006**, San Jose, CA (Jan 2006).

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2. Diamond Based Quantum Information Processing, S. Prawer (invited), Nanosingapore, Jan 10-13, 2006.

3. Diamond Based Quantum Information Processing, S. Prawer (invited), Sir Mark Oliphant Conference on Quantum Nanoscience, Noosa, Australia, 21-26 Jan 2006.

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7. Coherent Population Trapping in Diamond N-V Centers at Zero Magnetic Field, Charles Santori1, David Fattal1, Sean M. Spillane1, Marco Fiorentino1, Raymond G. Beausoleil1, Andrew D.Greentree, Paolo Olivero, Martin Draganski, James R. Rabeau, Patrick Reichart, Sergey Rubanov, DavidN. Jamieson, Steven Prawer CLEO/QELS, Long Beach, CA, May 22, 2006.

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